SPACE CLOCKS – WHY THEY'RE DIFFERENT

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Abstract

Atomic clocks for use in operational satellites such as GPS and MILSTAR are a breed apart from their terrestrial cousins. Like most space electronic packages, clocks will seem to be a generation behind the technology used in other applications. The reasons for this include the need for high reliability parts, radiation hardness, and mechanical design. Other key drivers in the designs include zero gravity, unattended operation, limited monitoring bandwidth, and limits on weight size and power. Clocks used in short-term space experiments can be closer in design to ground clocks, but are generally not usable for operational systems without extensive modifications.

INTRODUCTION

Satellites have included frequency standards since the beginning of the space age. The advent of systems such as TIMATION, TRANSIT, and GPS brought the need for better clocks. Spacecraft Atomic Clocks have been a key and unique parameter of the development and deployment of GPS. These clocks provide the high stability required for accurate navigation performance, and their development for space needed to provide the highest stability reliably for the years required from the satellite. It was more than a matter of simply putting a good ground clock on a satellite. The launch process involves high levels of vibration and acceleration, and there are radical differences in environment while in space that will upset most clock designs. Long life and error-free optimum performance within the limited size, weight, and power are all critical.

Space atomic clock technology makes accurate performance inherent in the system, but at the same time the reliability and operation of these devices in the system must insure continuity and integrity of performance. Investment in this technology is necessary to maintain commercial interest and viability for production. GPS is the dominant user of high precision and stable space atomic clocks; the only other users are the few MILSTAR satellites containing rubidium standards with relatively relaxed requirements. As such, GPS has been virtually the sole supporter of this technology, and NRL has been the leader in their development and application [1].

SPACE TECHNOLOGY

The principal objectives of atomic clocks in operational satellites are:

1. Stability and predictability of maintaining synchronization over the operational lifetime of the satellite,
2. Reliable continuity of the signal provided,

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Space Clocks - Why They're Different**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Naval Research Laboratory,4555 Overlook Ave SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001482. 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 Nov 2001, Long Beach, CA

14. ABSTRACT
Atomic clocks for use in operational satellites such as GPS and MILSTAR are a breed apart from their terrestrial cousins. Like most space electronic packages, clocks will seem to be a generation behind the technology used in other applications. The reasons for this include the need for high reliability parts, radiation hardness, and mechanical design. Other key drivers in the designs include zero gravity, unattended operation, limited monitoring bandwidth, and limits on weight size and power. Clocks used in short-term space experiments can be closer in design to ground clocks, but are generally not usable for operational systems without extensive modifications.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

3. Ability of the system operators to anticipate and prevent signal anomalies,
4. Ability of the system operators to diagnose anomalies for immediate corrective action, and
5. Programmatic issue of having adequate production source(s) of these devices.

These objectives add to the demands of designing for operating and surviving in the space environment. The developer would then need to take this into account in the overall unit design and in the nature of the validation test program to verify the design and ensure clock operation in the satellite integration, functional testing, and final in-orbit operation.

DESIGN ISSUES

Size, weight, and power are major factors in the design of satellite hardware. Satellites and even space stations will always be subject to these limitations. To justify large amounts of these scarce resources, the item must be very critical to mission success and there can be no easy alternative to using it. A laboratory hydrogen maser with a volume of over a cubic meter, weighing more than 100 kilograms and drawing over 150 watts, is unlikely to find a home in space if a rubidium clock a fraction of that size meets the requirements.

The issue for the space clock designer is to make a clock that meets his performance goals while minimizing size, weight, and power. That may force the designer to choices of exotic materials such as titanium to minimize weight while adding the strength needed to survive launch. In the example case of hydrogen masers, reducing the volume led to using smaller RF cavities with lower Q factors. That, in-turn, led to passive and q-multiplier operating modes.

LAUNCH ENVIRONMENT

One of the hardest initial problems in making a space clock is designing it to survive the launch. Launch environments vary widely depending on the payload and booster. The Space Shuttle, for example, is a manned mission and is designed to carry a wide variety of items to low-earth orbit. At the other end of the spectrum, sounding rockets are designed for short, inexpensive missions and often have very harsh rides. Missions such as the Global Positioning System fall in between, with typical accelerations up to 20 g's and random vibration levels up to 19.8 g's. Early in NRL's work on GPS, vibration tests were done on commercially available cesium and rubidium clocks [2,3]. All test units failed. The rubidium clock's glassware broke and numerous internal ceramic insulators failed in the cesium beam tube. Screws back out, large components break loose, circuit boards flex.

The remedies for the circuit board problems are well known in the space industry. Conformal coating of circuit cards is done to capture components and prevent them from resonating with the driving vibration forces. Circuit card mounting is designed to avoid long unsupported areas that can resonate at low frequencies. Wiring is bundled and secured. Some designers avoid the use of connectors; others use proven design connectors.

The more difficult problem is the physics unit. There the mechanics are not just issues of mounting components, but of providing radio frequency cavities with precision alignments. A structure might survive vibration in the sense of not coming apart, but still would not function as required.

Acceleration is not usually as significant as vibration, since it is rarely high enough to break anything.

However, if the standard has to operate through launch and meet performance specifications, deformation of cavities and misalignment of beams can be a problem.

ON-ORBIT ENVIRONMENT

Once the clock makes it successfully to orbit, it must be able to run properly in that environment for its design lifetime. The shorter the design life, the easier it is to make the clock. Additional complications are the lack of gravity and air. Reliability is particularly important in a space clock, since repair is usually impractical if not impossible. The key factors in stable operation and long life are: thermal control, parts selection, and radiation exposure.

ZERO G

The cesium and rubidium clocks flown to date have not been seriously impacted by the lack of gravity. There is essentially no effect on rubidium clocks, since the physics unit has no directed flow of atoms and no mechanically moving parts. Cesium beam tubes do have a beam of moving atoms, but the beam design for commercial tubes assumes no significant deflection of the beam by gravity. There have been some enhancements done in the cesium ovens to improve their operation.

With new technologies, such as cesium fountains, the picture changes. The classic fountain with a beam of atoms rising and then falling back won't work without gravity to pull the atoms back. However, the lack of gravity makes cold atom beam tubes interesting, since there isn't a force to deflect a slow moving beam.

ZERO PRESSURE AND THERMAL EFFECTS

The lack of air has two effects. First, structures such as vacuum enclosures containing RF cavities are designed to resonate with a given set of barometrically induced stresses. With no air pressure, the forces change and the resonance frequency will change as the cavity deforms. This effect was an early problem in hydrogen masers, which had large frequency offsets occur as weather fronts passed through. Most clocks, including crystal oscillators, have noticeable frequency shifts as they go from air to vacuum. A large part of that effect is really a thermal problem.

Electronic circuits are designed to be able to emit or transfer excess heat. Most circuits built for terrestrial applications use airflow as at least part of their thermal design. When there's no air to conduct heat away from components, either the heat travels by another path or the component overheats. As in the vibration issues, the aerospace industry has found solutions for thermal hot spots. Heat is either conducted away through solid paths or radiated to cooler surfaces. Thermal design is critical for reliability. The projected lifetime of an electronic part is directly related to its temperature. Some of the most difficult thermal design problems can be RF power circuits, where circuit design limits the use of conduction paths for heat. In such components, even though the device case temperature is within good design limits; the junction temperature inside may be critically high.

The thermal environment on an orbiting satellite is usually designed to be benign, with base temperatures near room temperature and only a few degrees excursion around the orbit. GPS has demonstrated that some of its clocks run better on-orbit than in the laboratory. It's not really that simple, though. Typically, a spacecraft electronic package must be designed to operate over a wide range of temperatures, because the

satellite thermal environment cannot be completely controlled and will change over time, usually getting hotter. A typical design range is 15°C to 45°C. That kind of range has a large impact on the design of ovens and heat conduction paths. A clock that will only run at 23 ± 2°C would be hard to sell to a satellite maker, since it places exceptional demands on his thermal design. He will be agreeable with designing for that range, but not with having the mission dependent on making it 100% of the time. One way around the problem is to design a thermal control package into the clock. The GPS Block IIR rubidium clocks have built-in baseplate thermal control that allows them to work well over a 10°C range.

The other performance aspect of thermal design is the stability of the clock as the temperature of its mounting plate changes. Reference clocks in high performance applications on the ground are usually in well-controlled environments. Long-term stability for time keeping is often greatly improved when temperature and humidity changes can be limited. The Naval Observatory, for example, keeps its clocks in environmental chambers where the temperature excursions are normally less than 1 degree and humidity is controlled to within 1%. The typical satellite temperature swing of several degrees peak to peak over an orbit can be significant. A temperature coefficient of $1\times10^{-14}/^{\circ}C$ is considered very good for current space cesium and rubidium clocks. A clock designed to be stable to parts in 10^{-15} with that kind of temperature coefficient would be seriously degraded. The solution can be a mix of reducing the sensitivity of the clock and adding thermal isolation hardware.

RADIATION

Radiation effects in clocks are unique to space. They affect the clock in several ways. The first is that they drive the parts selection and in some cases the circuit design philosophy. A part that fails or changes parameters outside of acceptable bounds due to radiation within the design life is not acceptable. Most semiconductors used in commercial clocks today are not radiation hard. Radiation also affects clocks in more subtle ways. A crystal oscillator used as a flywheel in an atomic clock will change frequency when hit with a burst of radiation. If the time constant of the control loop is longer than the time it takes the crystal to change frequency, the clock unlocks. Another effect is darkening of glassware. Darkening of the glass cells degraded early space rubidium clocks.

Radiation sensitivity is a parameter that impacts design life. A part that is acceptable for a 1- or 2-year flight experiment or demonstration is likely not acceptable for a mission with a 10-year design life. The parts selection issue drives two additional problems. The first is that hardened versions are not available for most semiconductor parts. The ones that are available are not usually the most recent parts. With most modern clocks being computer-based designs, the speed and memory available for ground use simply aren't achievable in space parts. The second problem is that even the parts that are available aren't usually available quickly or in small quantities. Major satellite programs work around this by encouraging designers for all payload boxes to use parts from a list of selected parts that the prime contractor will buy in quantity. The issue for the clock designer is that he must find ways to meet his needs with what he can obtain.

One other impact on clock design from radiation is the need to build in a method to recover from a burst of radiation. Military designers have concerns about manmade events, but even a clock in a commercial satellite must contend with solar flares and single event upsets. If the clock experiences a change due to radiation, the electronics must be able to correct it. Small radiation bursts may only limit the time constant of the servo loop. Larger effects require the designer to build in a method to recognize the upset and recover with minimal loss of performance. Microprocessors and their associated digital components are of concern, since changing a single bit in memory or having the processor lose its place in the program sequence can have disastrous effects on clock operation.

RELIABILITY

As mentioned previously, one of the major factors in the reliability of space clocks is thermal design. Another key factor is the selection of parts. Some parts such as plastic body semiconductors are inherently less reliable than others. Traditionally, parts for space electronic boxes were chosen from pre-approved lists published by NASA or other military program offices. With the recent trends away from military standards, these restrictions are less obvious, but the need to design with proven parts remains. It simply doesn't make sense to spend millions of dollars to launch a satellite that is likely to fail early.

Like the radiation-hardened parts, high reliability parts are difficult to obtain. Again, the solution has been to do block buys of common parts for a satellite system. And, again, the problem for the clock builder is getting the performance he needs from available components. The need to fly proven parts also limits the available technology to things that already have a good history. This tends to eliminate the newest, and often most attractive parts.

OPERATIONS

TELEMETRY

Clocks in a satellite environment need to be monitored, just as those we use here on earth are. The problem is the availability of useful information. In most satellites, telemetry data bandwidth is tightly controlled. The rubidium and cesium clocks flying in GPS only have a few of the internal analog monitors available in the data stream and these are a reduced resolution. Figure 1 shows an example of a GPS Block IIR rubidium clock's light monitor as it can be seen in the laboratory and, below, as it is seen through the telemetry outputs. The sharp breaks that indicate a frequency jump has occurred in the clock are clearly observable in the laboratory data (upper trace) and entirely missing in the telemetry stream (lower trace) due to available resolution.

The newer processor-based clocks have the potential to get around that limitation by providing data to the host vehicle in digital format. While downlink bandwidth will still be a limited commodity, the clock can be commanded to output the required data at a useful resolution at a rate compatible with the host.

A bigger problem with the telemetry is the overall usefulness of the downlinked data. The satellite operator needs simple indicators that let him know that the clock is either working properly or has failed. He wants to be able to trust the information he gets and doesn't want to have to do a lot of analysis. He'd also like to know how much life is left in the clock so he can plan for a smooth replacement when it nears end of life. These are problems for any clock. Those who have run cesium clocks know that the green lights on the front have been of limited value. While they rarely indicated a bad clock was good, it has been very common to see the "alarm" indicator lit on a reasonably healthy clock. The challenge for the space clock designer is to use to available state-of-health data to provide useful information. One possibility that has appeared in commercial digital clocks is the creation of a performance indicator that produces a value similar to an Allan deviation. It could give an internal indication of the stability of the clock.

Operating Experience

Another issue with space hardware in general is demonstrated ability. The designer of an operational satellite system such as GPS or MILSTAR will be very unwilling to fly unproven technology in a function critical to mission success. The problem is how to gain experience with a technology in space that has no experience base.

There are several approaches to the problem. First, a technology such as cesium-beam or rubidium gas cell clocks that has extensive operational use in terrestrial applications has a big advantage over an all-new concept. The issues with these clocks have been primarily engineering. For a concept such as optical pumping, ion storage, or cold atoms, the problem grows into convincing the user that the technology works anywhere outside the laboratory. There are no widely used clocks generally available using these technologies. Here, the approach that makes the most sense is a multi-step process where new ideas are demonstrated on technology satellites or experiments on other satellites before being used in operational systems. Good examples of this process are the Navigation Technology satellites flown by NRL that demonstrated the rubidium and cesium clocks now used in the operational GPS system **[1,4]**. The PARCS experiment **[5]** on the International Space Station is another excellent way to get a feel for the way advanced concepts can work in the space environment.

On-Orbit Analysis Tools

Performance of the clock on-orbit needs to be monitored, preferably independently of the spacecraft function the clock supports. That is, if the clock is used as the time and frequency reference for a communications system, it is desirable to monitor the time and frequency of the clock by a means other than whether or not the communications system works. In GPS, the monitor station data are processed by NRL to determine the phase of the clocks over time **[6]**. This process is done by comparing the measured pseudoranges and computed positions from the post-fit NIMA orbits to determine the true offset and stability of the clock. Other applications will require different approaches, but the ability to monitor the clock's performance is crucial to using it successfully.

TESTING

Space electronic packages are rigorously tested at the time of manufacture and when integrated into the vehicle. The impact on the usefulness of the satellite is too high to take unnecessary risks. The trade-off is the additional cost and schedule time needed to do the testing. The philosophy issues of testing satellite hardware extend to the clocks. No one wants to launch a package with known problems. Even worse, no one wants to realize after launch that the testing done was not adequate to detect problems. A commercial clock maker will balance the risk of delivering a bad clock to a customer with the cost of replacing it under warranty. A laboratory clock is usually built in a process where design flaws are detected and corrected over its life. Neither of these approaches works well in space.

Space hardware testing is broken into two phases **[7]**. The first is qualification. Here, the design itself is tested at levels of stress higher than expected in operation. The idea is to verify that the design works and has adequate margin for production and normal use. The next phase is acceptance testing. The concept for acceptance is that the design is already proven; what needs to be done is to verify that this particular unit has no manufacturing defects. For this concept to work, the manufacturing process must be carefully controlled so that there is no question that the unit under test was built to the design that was qualified.

Acceptance testing is designed to find things like bad solder joints, bad parts, and improper setup. If a design problem is discovered in qualification, the qualification test is redone on the modified design. If a problem is discovered in acceptance testing and is clearly not a design issue, the acceptance test is repeated on the repaired unit. The issues that arise in these tests are which tests in the test sequences have to be repeated. For instance, if clock fails the stability test in thermal vacuum and has a component replaced, does the vibration test have to be repeated? The conservative approach is that the whole sequence is repeated, because the clock had to be at least partially disassembled and reassembled to repair the problem. In practice, when money and schedules are tight, there is a rationalizing of the risks and less stringent sequence is sometimes done. The clock designer should design with testing in mind. Things like making internal monitors externally accessible can make it easier to determine what's right and wrong with a clock after assembly and initial testing.

A more recent testing challenge is testing embedded software. There are standard techniques for finding unexpected states and outcomes in digital hardware, but the process for testing embedded software in systems for these conditions is still in its infancy. Hardware and software must be analyzed as a system, because the software executes in response to external events; that is, the correctness of a computation depends on its input. System qualification must include a methodology that models the complete system, hardware and software. Performance verification must be supported by an analysis as well as test, and should be a required part of the qualification process.

Another issue in testing is how much is done by the factory and how much is done by the customer. Most vehicle contractors will require the clock maker to perform acceptance testing prior to delivery. Normally, the clock will tested again over a more limited set of parameters after delivery and then once more as part of the satellite when it's integrated. These sorts of tests are usually functional tests to determine if the device still works. The performance is not evaluated, so it is difficult to tell if the unit still works as it should. The issues here are the cost and time required for the testing. The concerns are that tests like spacecraft vibration have a cumulative effect on the clock.

Life testing is an approach to resolving the lack of flight experience in a design. GPS Block IIR rubidium clocks were an all-new design with no flight experience. A life test program was designed for these clocks at NRL to reduce the risk of flying them and to gather information about how they operated that could be used by the GPS operators [8]. In a strict statistical sense, such a life test has limited value, because the number of clocks tested is small. What can happen is that an early failure of a single clock in a small set will drive the statistics to indicate a very poor lifetime prediction. On the other hand, lack of failures in a small number of clocks does not completely prove that clocks are unlikely to experience problems. What these tests really accomplish is to give the system designers and operators a detailed sense of how the clocks will run over a long period of time. As mentioned earlier, the available telemetry from a clock in a satellite is sparse and has poor resolution. A test on the ground can be highly instrumented to include factory test points, high-resolution measurements, and tight environmental controls. In addition to normal operations, it is also possible to generate unusual test scenarios that will occur rarely in-orbit, such as voltage bus jumps, large temperature excursions, and bad command sequences. This capability allows detailed re-creation of problems seen on-orbit and also allows controlled testing of anticipated situations.

SUMMARY AND FUTURE PROSPECTS

Space clocks really are different. In general, they are harder to build, they must work in an unusual environment, and failures are not just warranty issues. Table 1 summarizes the differences. One of the consequences is that space clocks are more expensive, usually by a factor of at least 10. Consequently, there aren't very many. Higher production volume could reduce the costs, but at this time, only GPS and

MILSTAR fly atomic clocks. The limited demand means a very limited number of suppliers. The market is sporadic at best and there is no guarantee that the clock purchased a year ago will available next year.

	Radiation Hardening	Thermal Design	Reliability	Quality	Vibration	Testing
Ground	No	Relies on Air	Warranty	ISO Standard	Limited	ISO Standard
Space Experiment	Limited	Limited	Limited	One of Kind	Survival	Detailed
Space Qualified	Thorough Analysis	Thorough Analysis	>7 Years	Full Documentation	Fully Qualified	Full Test Sequence

Table 1. Comparison Matrix.

GPS is also proving to be its own worst enemy in the case of clocks. GPS needs very good space clocks. The availability of highly accurate time from GPS means that not only are ground users becoming dependent upon inexpensive GPS receiver vice expensive atomic clocks, but other space users can use GPS on-board instead of a space atomic clock. The absence of those needs from the market makes it more difficult and expensive for GPS to obtain flight clocks. Cost, schedule, and development factors deter the use of newer clock technologies. At the same time, the obsolescence of parts and manufacturing methods makes it difficult to buy the old ones.

The situation is aggravated by the government's approach to buying satellite systems. That approach makes the contractor responsible for the system working and leaves most of its design to him. The idea seems reasonable, but the problem is that there is no continuity. The prime contractor that builds one block of satellites may not be the one who builds the next. Each contractor will use his own best engineering judgment and may well pick different clock vendors. The end result is too little demand spread over several sources. No one source gets the resources or continuity of production needed to sustain them.

Several solutions have been discussed. One is for the government to buy clocks and supply them to whoever builds satellites that need them. That could focus the effort better, but has in the past relieved the satellite contractor of the responsibility for a key system component and subsequently the system performance. This approach has presented major problems in contracting and sticky legal issues. An alternative approach in today's changed government-industry environment may be possible in giving the contractor more flexibility in design participation and accepting units by test or other such means. Such a government provided approach could mitigate responsibility issues. But even with a single vendor getting all the business, that may not be adequate to support a viable source and has the downside of relying on a single small company for a critical component. Another approach is for the government to actually build the clocks in a government lab. That solves the problem of keeping a vendor going, but still raises concerns prime contractor responsibility.

There probably are no 100% solutions. Until, and if, the market for space clocks grows to the point where vendors can see enough business to justify their continuing investment to produce space clocks, the government will have to play a significant part in the process. Currently NRL supports the GPS Joint Program Office for clock development with a roadmap program for future clocks that provides engineering work for vendors and designs clocks for future use in the program [9]. NIST and the Aerospace Corporation also provide technology support.

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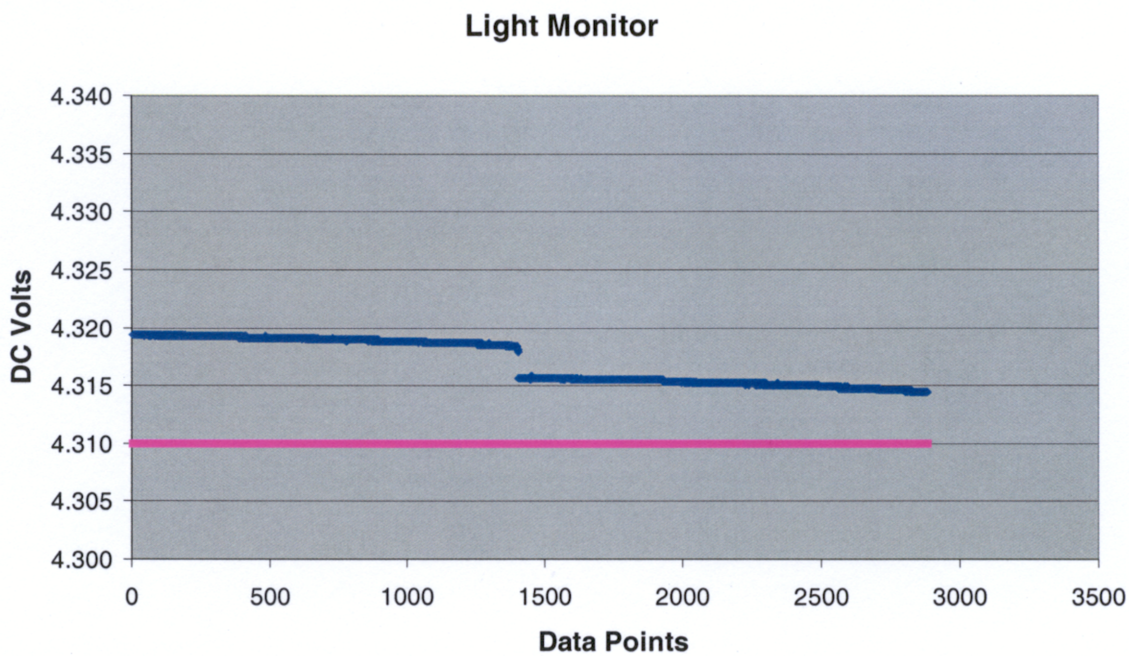

Figure 1. Telemetry Example.

QUESTIONS AND ANSWERS

DEMETRIOS MATSAKIS (U.S. Naval Observatory): I just wondered if you have any statistics on how often those different criteria actually fail when people try to go to space. Like how often do vibrations kill a clock, despite having done all those tests?

JOE WHITE: Once they get launched, if you do it right, very rarely. The first vibration test on a new design almost always fails. But once you have been through the qualification process, generally you do not have problems after that.

MATSAKIS: [Inaudible]

WHITE: Yes, more or less. If you do the qualification design properly and you have got your quality work, your standards for building the clock in place will have relatively few problems. You will have some statistical outliers as things go along. You do not see many major problems.

MICHAEL GARVEY (Datum TT&M): One thing that often gets neglected, and the guys at NRL are big proponents of it, is life-testing.

WHITE: Yes.

GARVEY: ... It is expensive, it takes a long time, it needs to be started early, and it is one of the first things to get cut.

WHITE: And, statistically, it is a problem because you life-test on a small number of units.

GARVEY: Right. But it is where you pick up some of the long-term reliability problems that do not come out of analysis.

WHITE: And the design features, things that you sort of designed into it, but you did not realize were going to work quite the way they do.

GARVEY: Right.

JIM CAMPARO (The Aerospace Corporation): Could you say anything about mean time between failures for space-qualified clocks? What experience we have, and what we might know about that?

WHITE: There is a lot of GPS experience, and it doesn't fit the traditional mold. I don't know if I have got enough time to really get into it. The problem with most of the clocks that GPS flies is that the physics units do not have the statistical background that you have on a commercial clock to come up with these kind of numbers. The circuit boards you can do that for, and generally that is not where the failures are. The failures tend to be things like running out of cesium, radiation effects you didn't quite expect, particularly in the early days of GPS. So there are lifetime numbers, and typically it is years for those kinds of things, but it is a very complex process. Let's talk off-line.